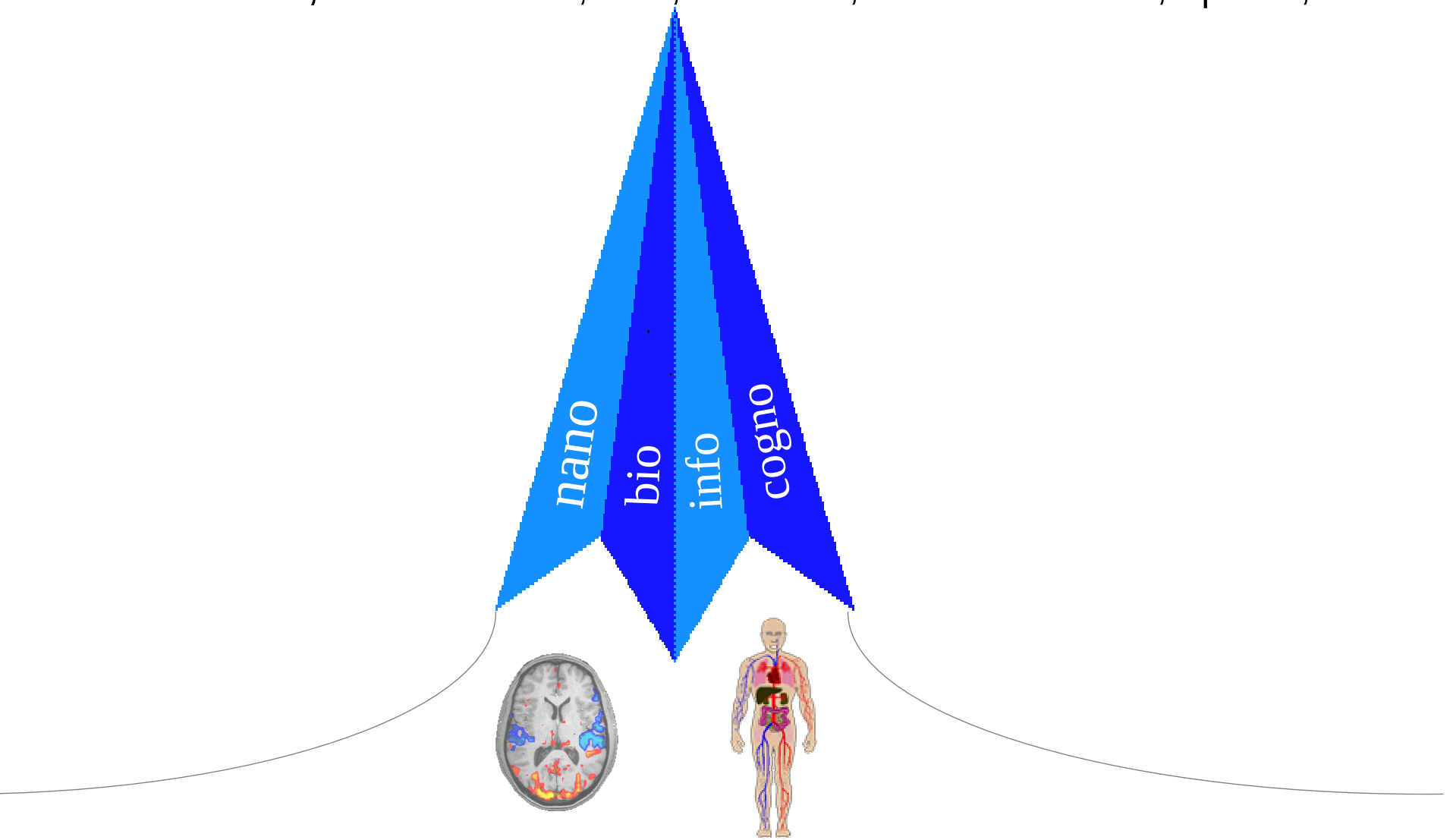
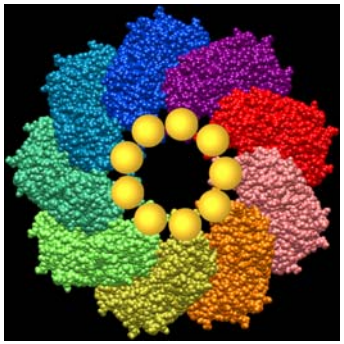
Dr. M.C. Roco, Senior Advisor, NSF, and Chair, US NSTC / NSET, April 22, 2004



The Emergence and Policy Implications of CONVERGING NEW TECHNOLOGIES

Topics

- **Relevance of nano-bio-info-cognitive (NBIC) integration**
- **Converging new technologies and policy implications**
- **Seed R&D programs**
- **Future challenges**



Idea

Advancing an integrative approach for converging S&E from the nanoscale and system levels,

- **with re-focus on people**
- **new NBIC platforms for science and technology**
- **co-evolution of new technologies and human potential**

Implications in key areas:

- *revolutionary tools and products*
- *everyday human performance: work efficiency, accelerated learning, better use and increase the individual, group and societal capabilities (to be happier, healthier and more productive) ,*
- *changing organizations and business, reshaping the infrastructure, R&D planning, societal issues*

Broad opportunity

2000 →

- **Material unity at the nanoscale and technology integration from the nanoscale, beyond the "Renaissance ideal"**

  Connecting disciplines and providing cause and effect explanation from nanoscale phenomena to culture is now possible

- **Powerful transforming tools (NBIC) developing at the confluence of disciplines, integrated from the nanoscale**

  Ability to analyze large, complex, hierarchical systems
  New paradigms for Nano-Bio-Info-Cognition

- **Improvement of human performance becomes possible**

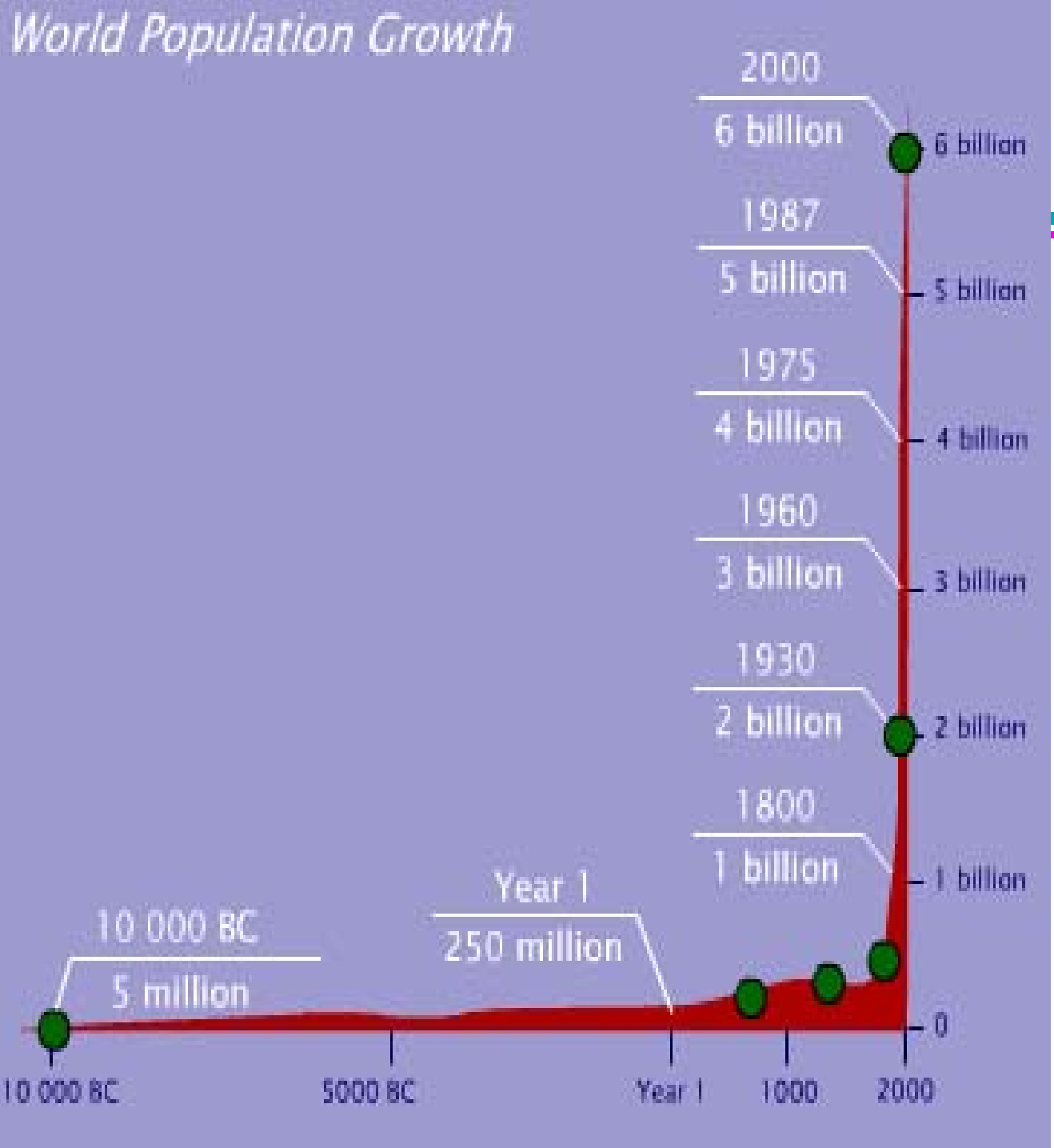
  Ex: measure signals from nervous system, condition and repair subcellular structures or regenerative medicine, adapt to change, collective capabilities

- **Adapting organizations and business**

- **Need for anticipatory measures** ('learning before doing')

  For deliberate choices in R&D, production, and policies

M.C. Roco, 4/22/04



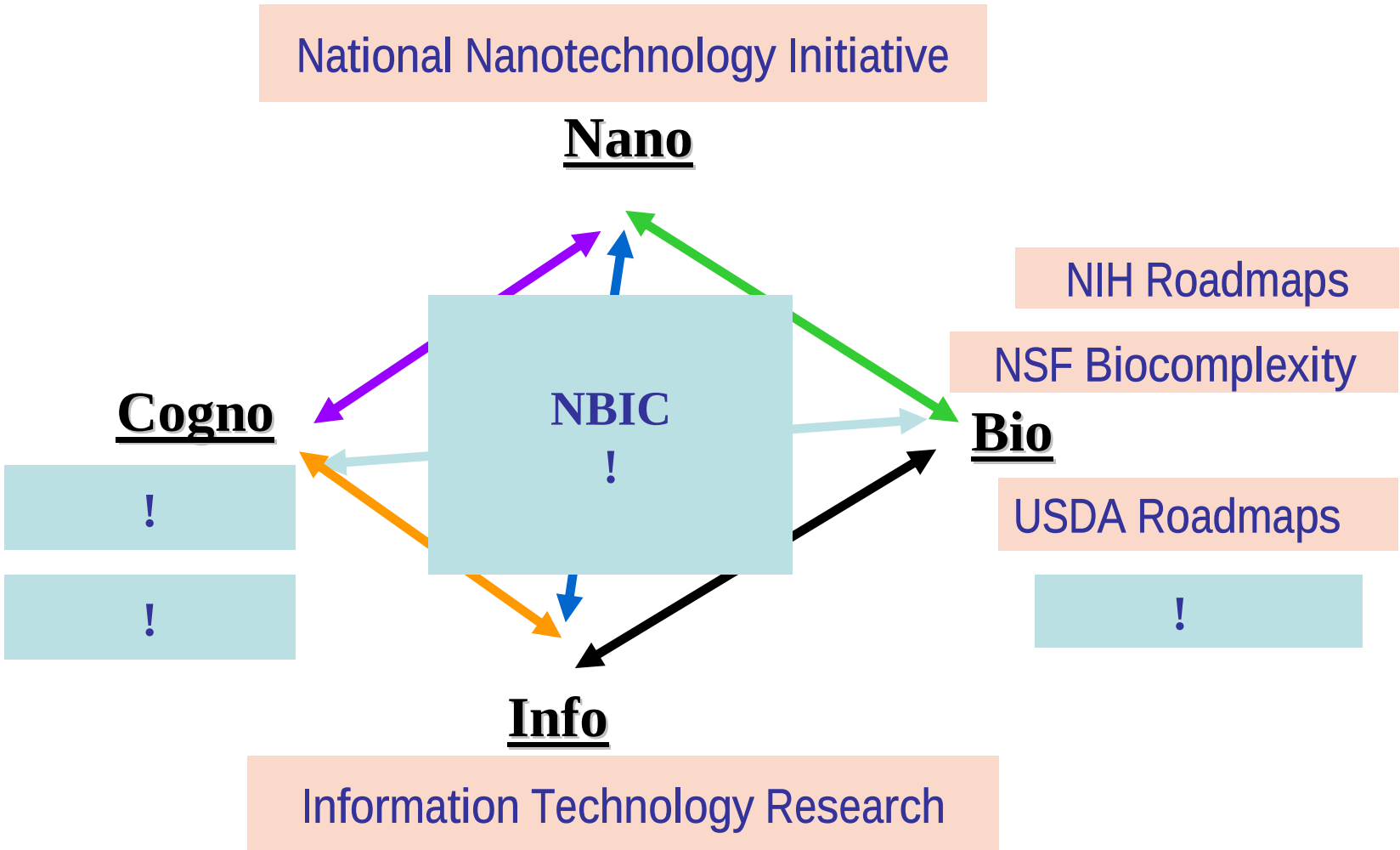
More people

9-10 billion by 2050

- Increased consumption of water, food, energy
- Changing environment
- Changing society
- Maintaining peace

NEED OF RADICALLY NEW TECHNOLOGIES

NBIC transforming tools (overview in 2000)



Four NBIC poles:

Convergence at nanoscale and information domains (*the push*)

The same fundamental principles and tools, same core elements for analysis (atoms/molecules or bits/parts), phenomena are interconnected, no need for discipline-specific averaging techniques

Realizing the human potential (*the pull*)

Determines bio and cognitive key challenges

NBIC convergence and integration

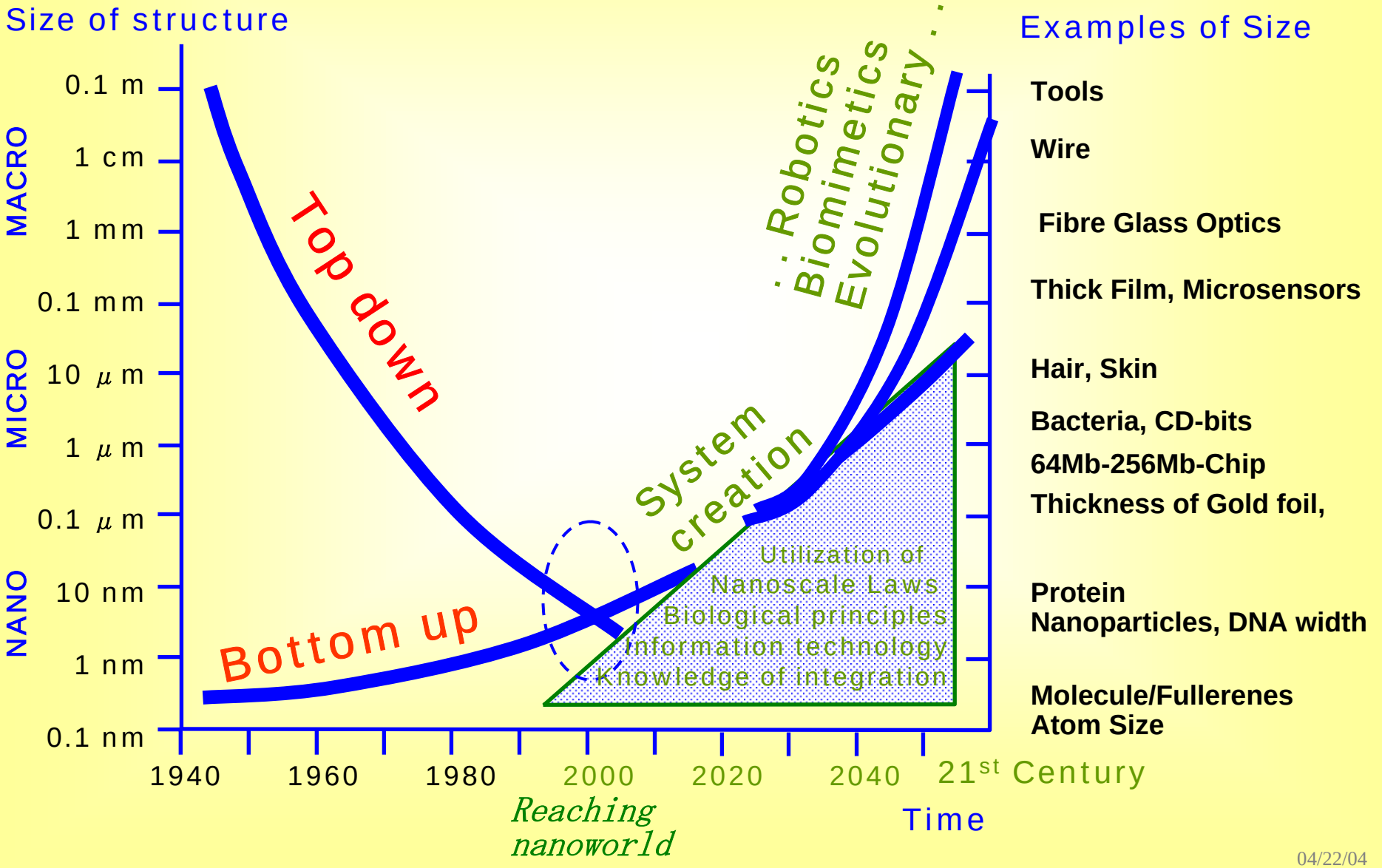
Requirement: Respect human dignity and integrity, the right to welfare

Confluence, with divergence / covergence in S&E

Ex. convergence: Renaissance – unifying macroscopic sciences;
Microscale – understanding & simulations by components;
Nanoscale – unity of matter

Ex. divergence: Specialization by narrow disciplines;
Digital vs. analogue platforms; Technology vs. societal acceptance

Reaching at the nanoscale



Timeline of significant augmentations to human performance:

improving our ability to collectively improve ourselves

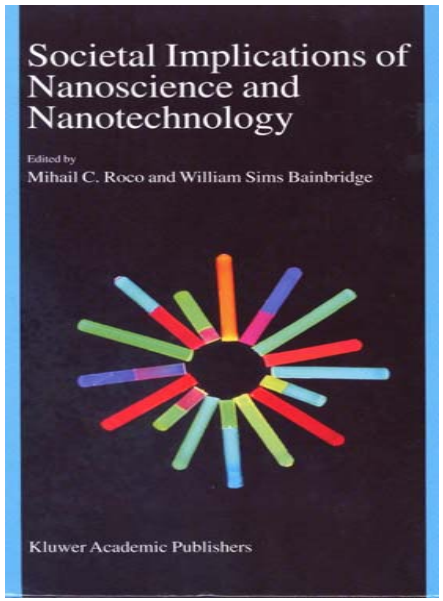
Generations	Key Advancements (human kind, transforming approach, tools and technology)
- m	Cell, body and brain development
- 100,000	Old Stone Age (Paleolithic), Homo Erectus, speech
- 10,000	Homo Sapiens, making tools: practical approach
- 500	Mesolithic, creating art
- 400	Neolithic, agriculture, writing, libraries
- 40	Universities
- 24	Printing
- 16	Renaissance in S&T, accurate clocks: abstract approach
- 10	Industrial revolution
- 5	Telephone
- 4	Radio

Timeline of significant augmentations (cont.)
(since the second WW)

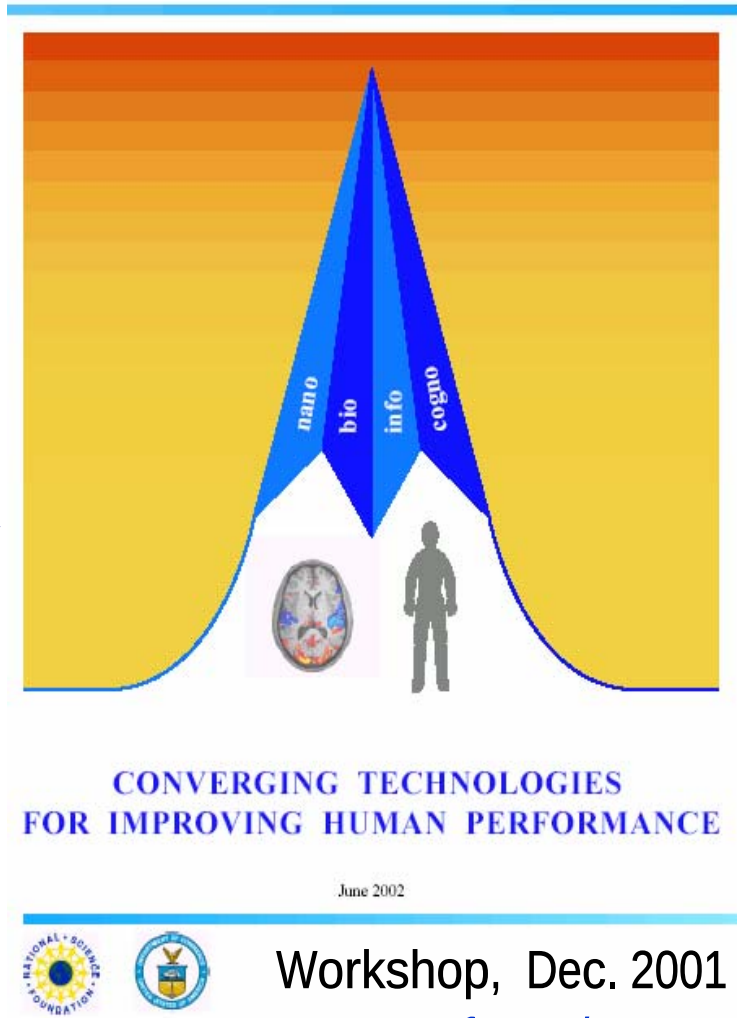
-3	TV
-2	IT: Computers
-1	BIO: Microbiology; Internet
0	NANO: Control at the building blocks of matter: fundamental approach Biotechnology products; Global connection via Internet
0.5	COGNITIVE sciences based on brain and social understanding NBIC: Unifying knowledge from the nanoscale and using global networking; Nanotechnology/Bio/Info products.
1	Converging technology products for increasing human potential (new products and services, brain connectivity, sensory abilities, innovation age, art understanding, etc.) "New industrial revolution" based on molecular / nanoscale control; Reshaping organizations and business
n	Evolution transcending human cell, body, and brain?

Converging Technologies (nano-bio-info-cognition) for Improving Human Performance (2001-2002)

"Coherence and divergence in mega trends in science and engineering"
1999-2000



Workshop, Sept. 2000
www.nsf.gov/nano
(Revisited in 2004)

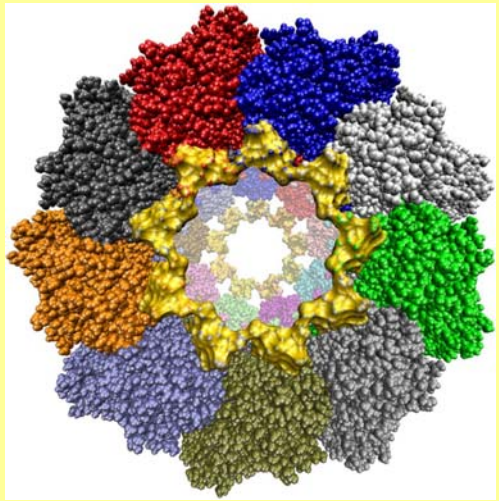


Workshop, Dec. 2001
www.nsf.gov/nano
Kluwer Acad. Publ

Coevolution of Human Potential and Converging New Technologies

(Feb. 2003 and Feb. 2004 meetings)

Topics:



Converging technologies and future society

Transforming tools

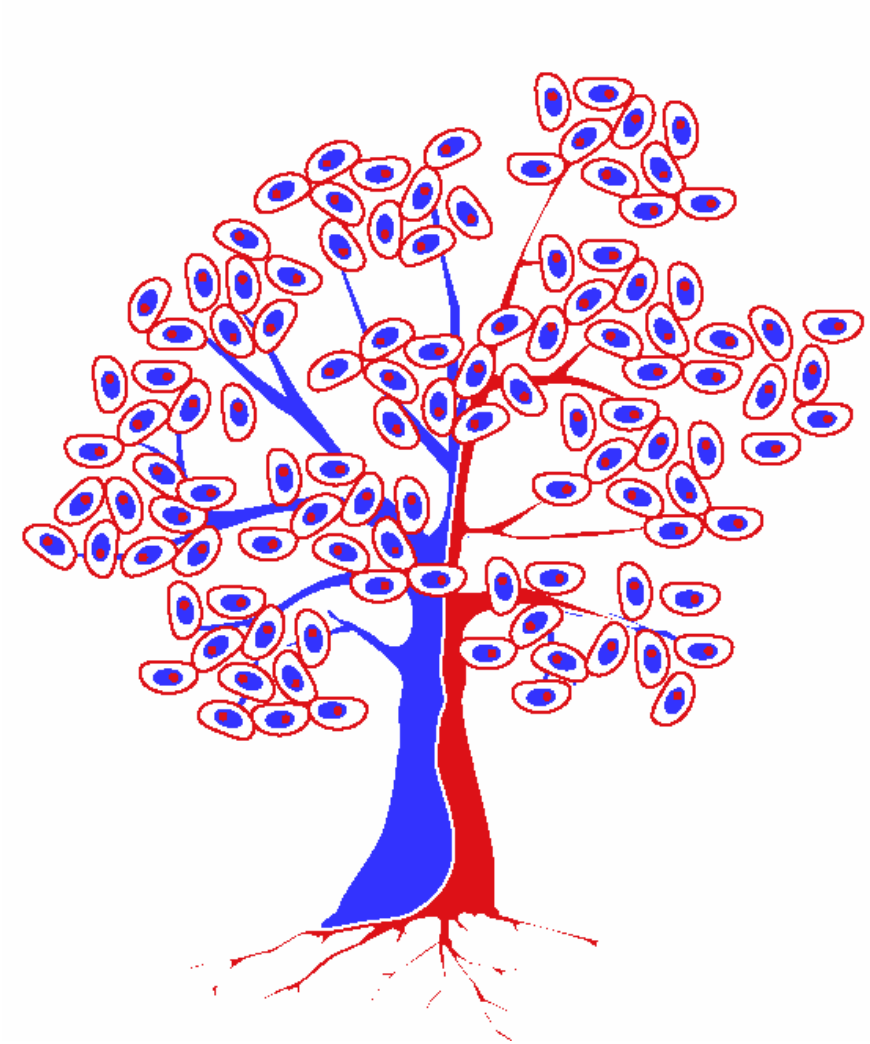
Education

Coevolution human potential – NBIC – business

In: Annals of the New York Academy of Sciences, Vol. 1013, 2004

Note: International perspective affected by the cultural trends

Vision for 2020: Regenerative medicine (2004)

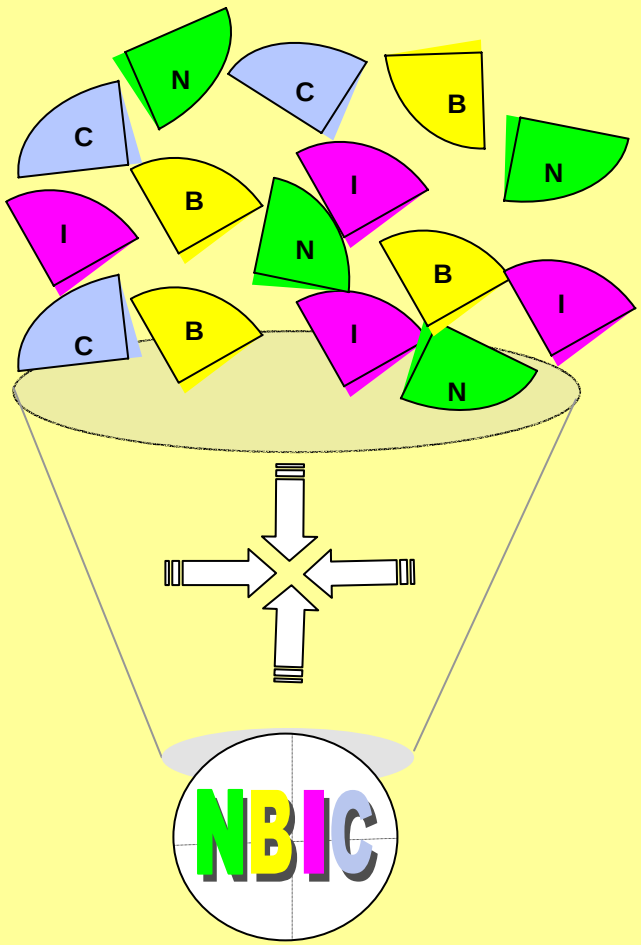


Combine precision assembly of matter (nanotechnology), building blocks of living systems (biotechnology), spatio-temporal flow of information (IT), and cognitive sciences.

Working group of 6 Federal agencies (NIH, FDA, DOD, NASA, DOC, NSF)

Draft report in Jan. 2004

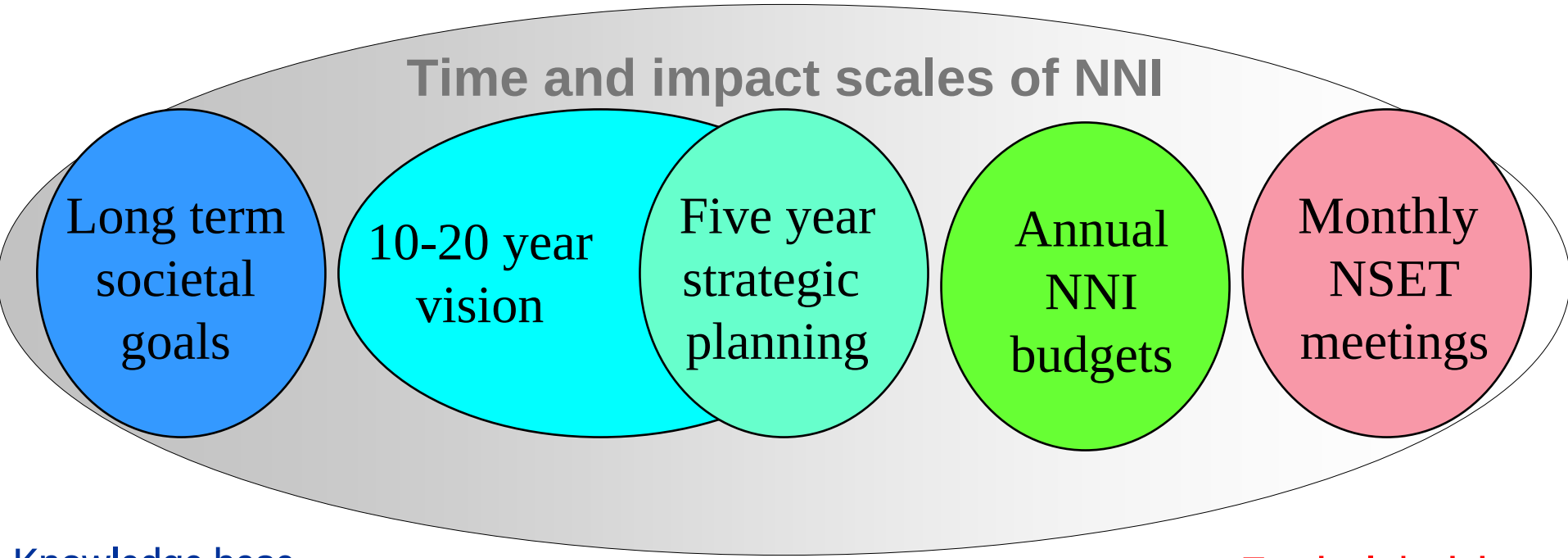
Commercializing and Managing the Converging Technologies (2004)



NSF sponsored workshop (September 2003) and report (April 2004)

Northwestern University, Center for Technology & Innovation Management (CTIM)

Ex.: The long-term vision drives NNI



Knowledge base
New technology
Human potential
Responsible NT

1999 Research Directions I
2004 Research Directions II
10 topical reports in 03-04
Evaluation PCAST, NRC

Annual budgets
FY 2001, .. , 2005
OMB crosscut
EOP evaluation

Tactical decisions
Programs
Partnerships
Safety issues

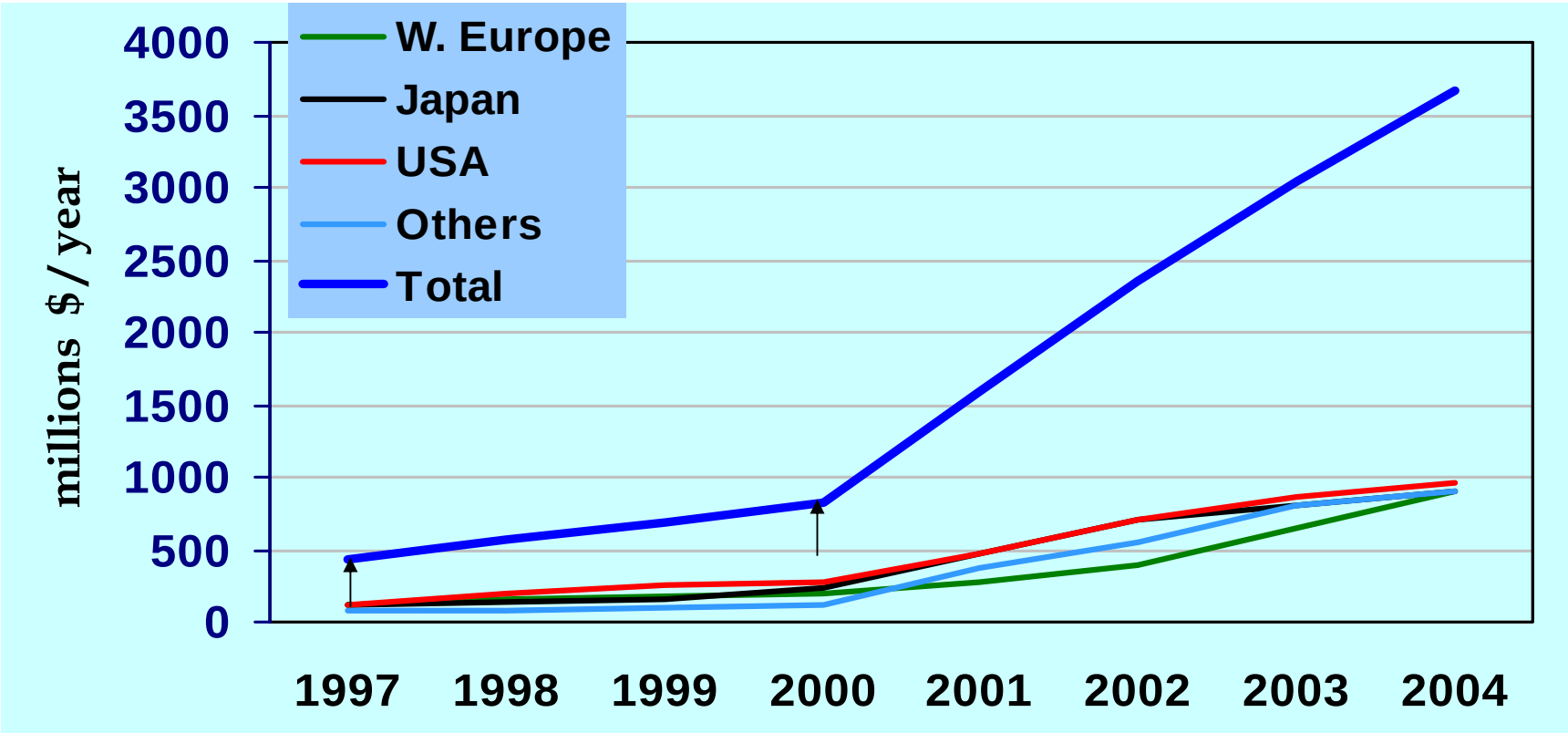
Ex: NNI – a coherent plan at national level
R&D Funding by Agency

Fiscal year (all in million $)	*2000*	*2001* Enact/actual	*2002* Enact/actual	*2003* Enact/Actual	2004 Req./ Enact	2005 Req
National Science Foundation	97	150 /150	199 /204	221 /221	249 /254	305
Department of Defense	70	110 /125	180 /224	243 /322	222 /315	276
Department of Energy	58	93 /88	91.1 /89	133 /134	197 /203	211
National Institutes of Health	32	39 /39.6	40.8 /59	65 /78	70 /80	89
NASA	5	20 /22/	35 /35	33 /36	31 /37	35
NIST	8	10 /33.4	37.6 /77	66 /64	62 /63	53
EPA	-	/5.8	5 /6	5 /5	5 /5	5
Homeland Security (TSA)	-		2 /2	2 /1	2 /1	1
Department of Agriculture	-	/1.5	1.5 /0	1 /1	10 /1	5
Department of Justice	-	/1.4	1.4 /1	1.4 /1	1.4 /1	1
TOTAL	270	422 /464.7	600 /697	770 /862	849 /961	982
		+72%	+50%	+24%	+15%	

Other NNI (NSET) participants are:
OSTP, NSTC, OMB, DOC, DOS, DOT, DOTreas, FDA, NRC, DHS, IC

Ex: Context – Nanotechnology in the World

Past government investments 1997-2004 (est. NSF)



Note:

- U.S. begins FY in October, six months in advance of EU & Japan (in March/April)

Converging New Technologies
Envisioned Implications

A. **Expanding human cognition and communication**

B. **Improving human health and physical capabilities**

C. **Enhancing societal outcomes, including new products and services**

D. **National security**

E. **Unifying science and education**

F. ***Reshaping business and organizations***

G. ***Policies for R&D, new investments for S&E platforms and infrastructure***

A. Expanding Human Cognition and Communication

- **Improving cognition, and cognitive evolution**
- **Understanding brain functions; brain-machine-brain interactions; and group communication**
  Ex: unveil the memory, thinking and emotional capacity of the nervous system
- **Spatial cognition and visual language using converging technologies**
- **Portable IT "personal broker"**
- **Enhanced tools for learning and creativity**
- **Predictive science of societal behavior**

Understanding and Simulating the Brain

Ex: Neuron-to-neuron interactions via the neurovascular approach

R.R. Llinás and V.A. Makarov, NYU

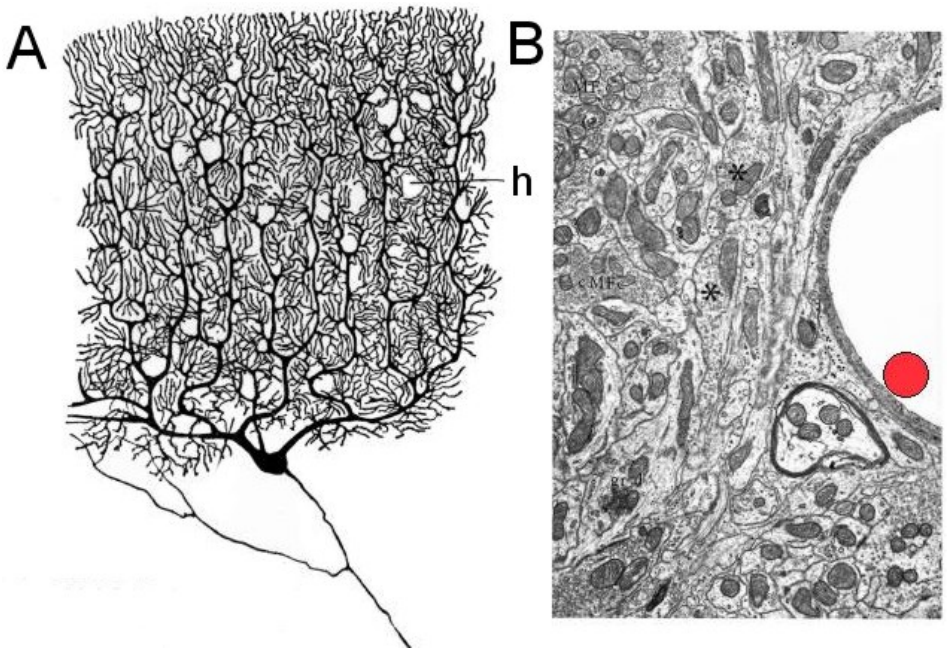


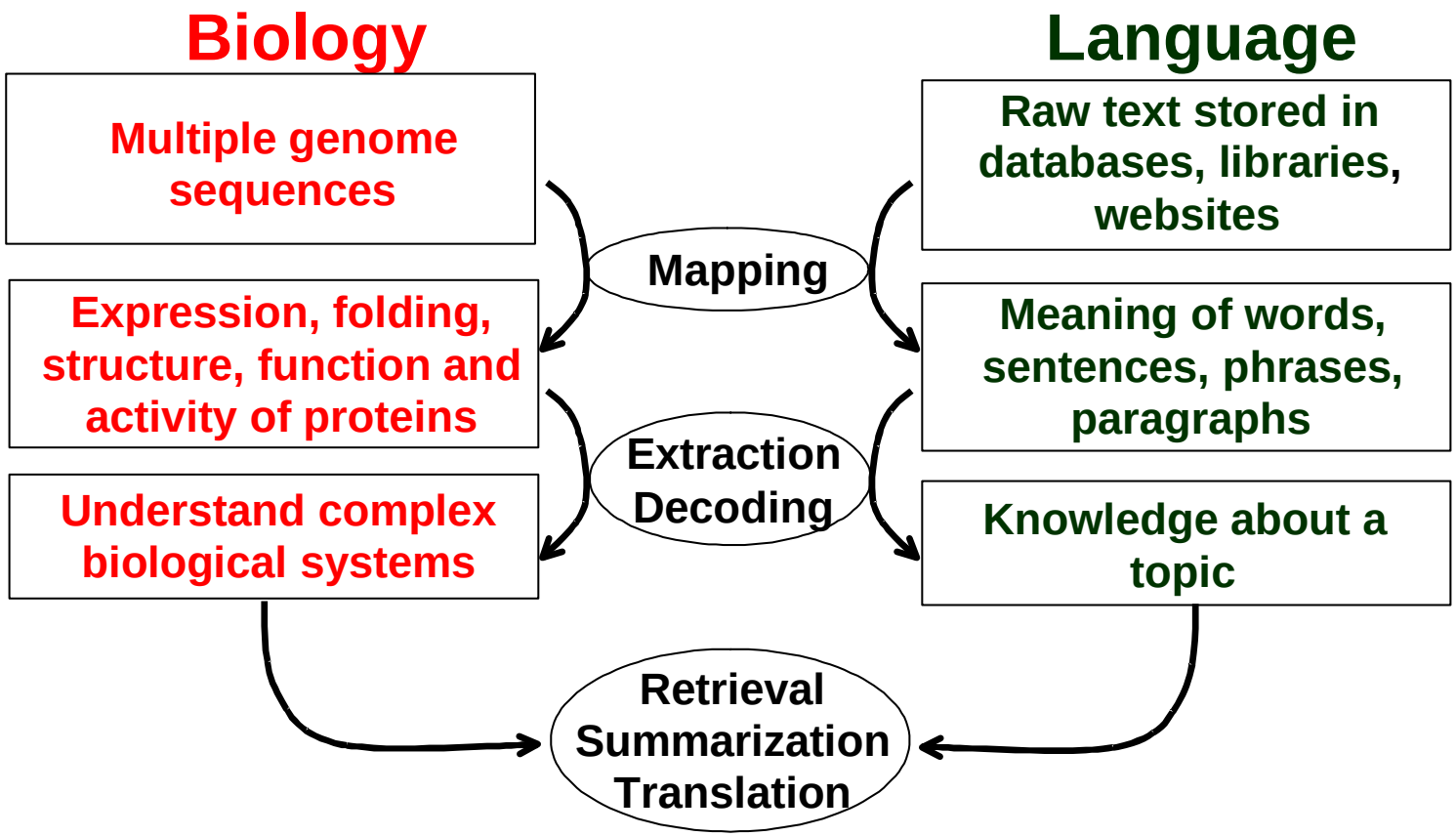
Illustration of comparative size scales for a neuron,a capillary and an n-wire.

A. Purkinje cell with dendritic tree penetrated by many capillaries foramen
B. Elentronmicrograph of a corresponding site in the dendritic as shown in h with a 1µ electrode (red spot) drawn inside a capillary.

(NBIC Report, 2002)

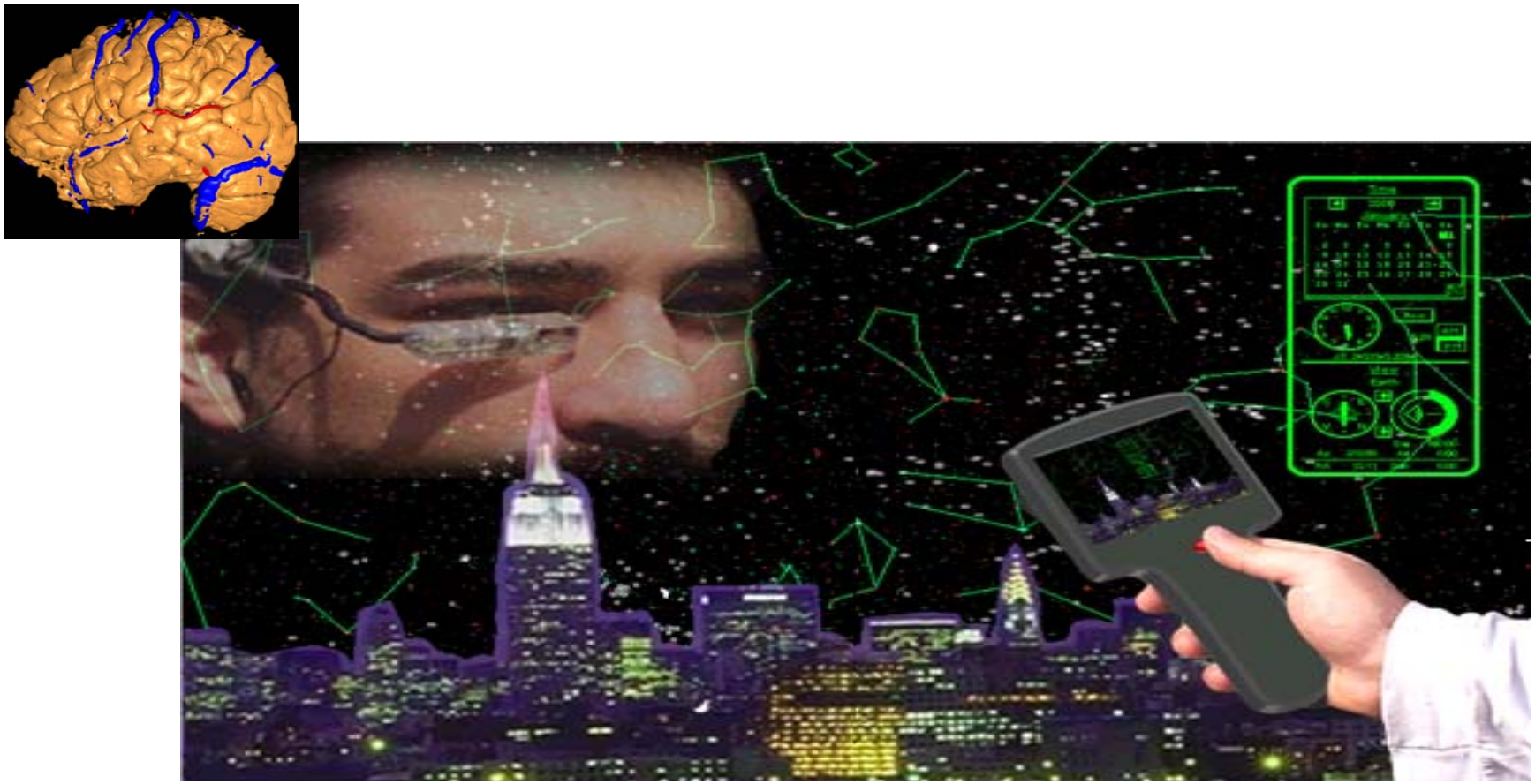
Analogy between biology and language

forms the basis for the convergence of computational linguistics and biological chemistry



J. Klein-Seetharaman, 2002 in the NBIC Report

Vision of the world as a distributed, interconnected "brain" with various architectural levels



Based on individual rights to privacy, access and progress

(NBIC Report, 2002)

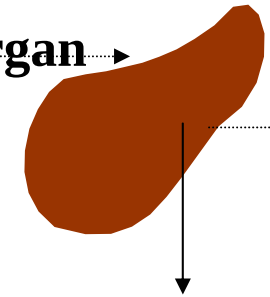
B. Improving Human Health and Physical Capabilities

- **Bio nanosystem approach for healthcare, regenerative and biocompatible body replacements, and physiological self-regulation**
- **Brain-machine interfaces, and neuromorphing engineering**
- **Improving sensorial capacities and expanding sensorial functions**
- **Improving quality of life of disabled people**
- **Aging with dignity, and life extension**

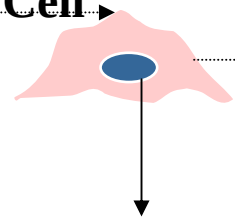
Examples of levels for intervention of nanobiotechnology *in **human life extension***

Human

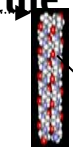
Organ



Cell



Molecule



- Joint replacement
- Non-invasive and invasive diagnostics for rapid patient monitoring
- Cognitive-assist devices
- Targeted cancer therapies

- Artificial organs
- Sensors for in vivo monitoring
- Localized drug delivery
- Neural stimulation
- Cardiac therapies

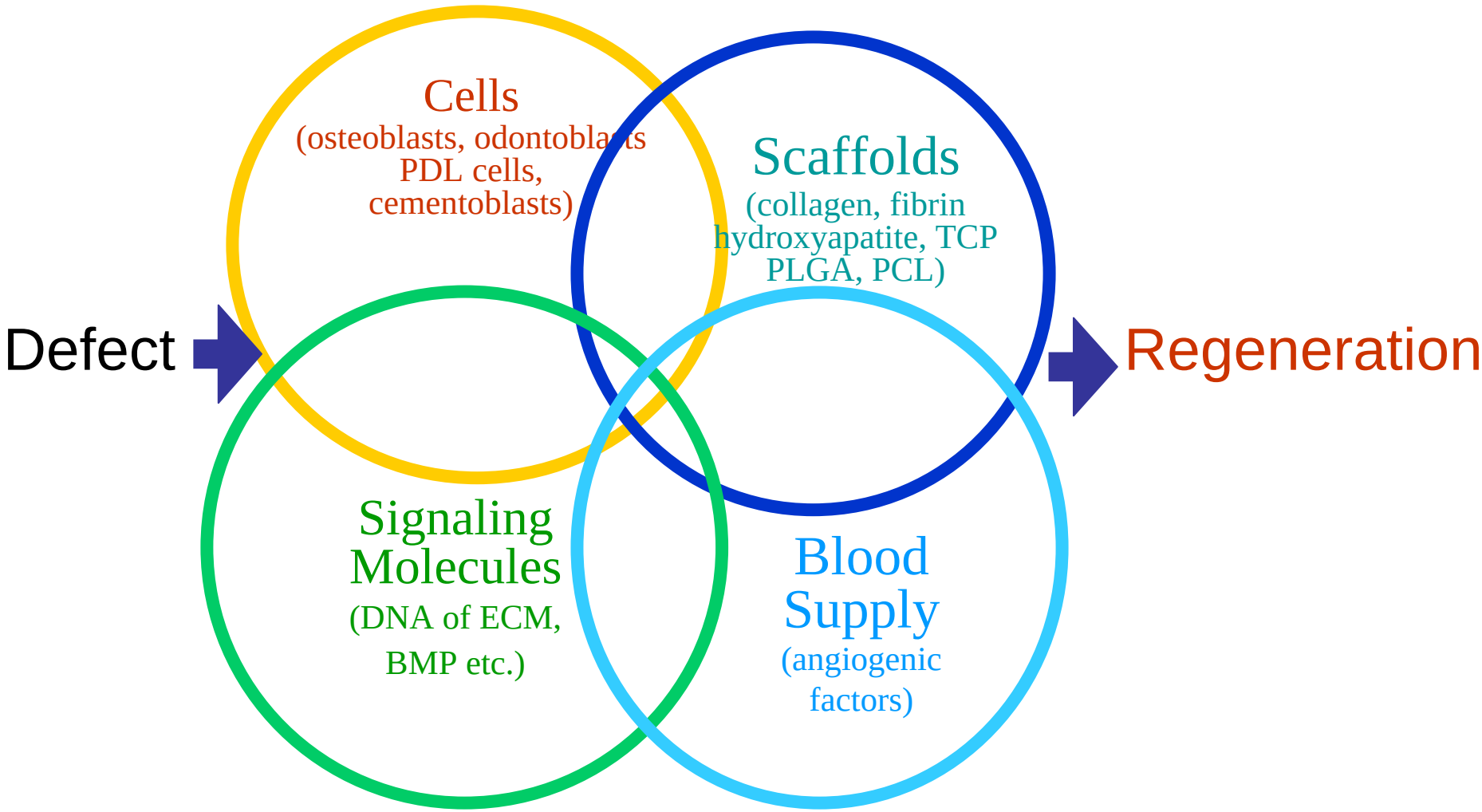
- Improved cell-material interactions
- Scaffolds for tissue eng.
- Genetic therapies
- Cell ageing
- Stem cell therapies

- Localized drug delivery
- Gene therapy devices
- Self-assembly structures
- Fast diagnostic techniques

(NBIC Report, 2002)

Regenerative biosystems from the nanoscale:

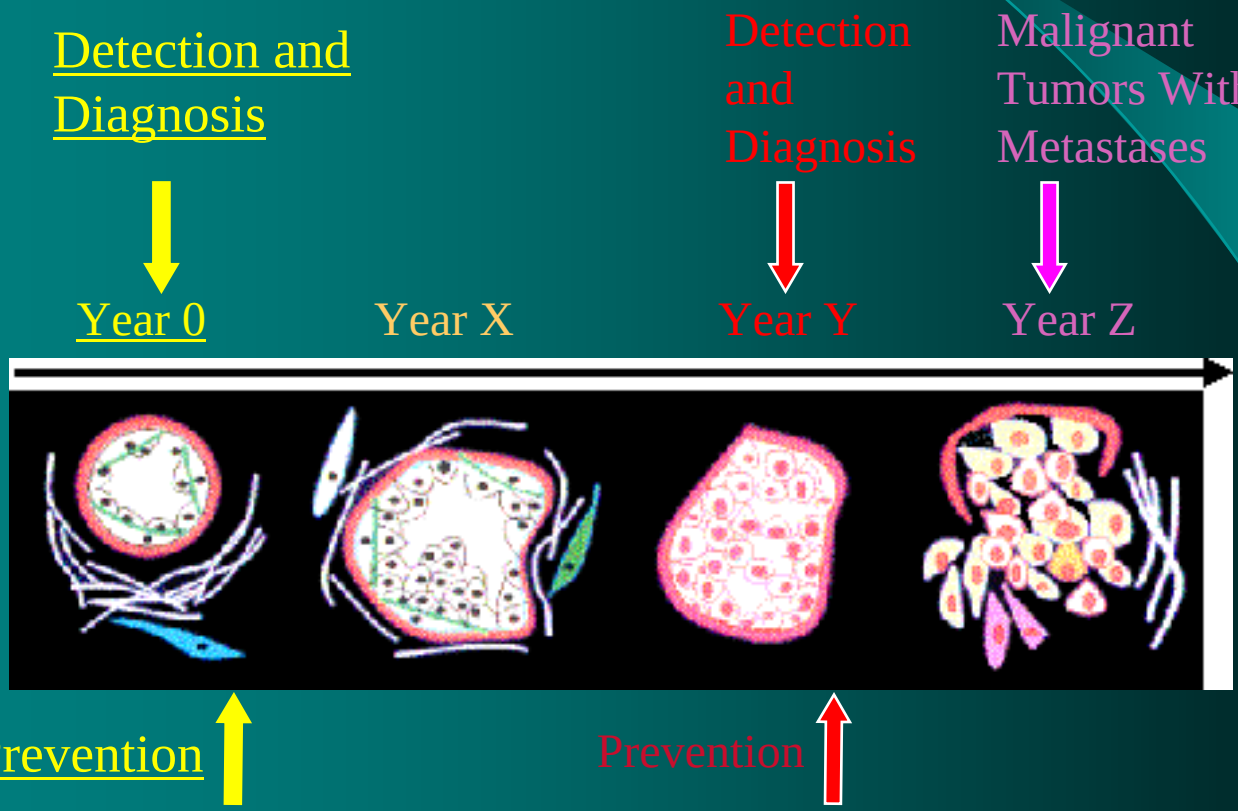
nanotools, bioprinciples, information control, and ethical aspects



Challenge: To Eliminate Suffering and Death Due to Cancer – 2015

"A Vision Not a Dream!" by using nanotechnology, A v. *Eschenbach, NCI*

Where We Want To Be ← Where We Are



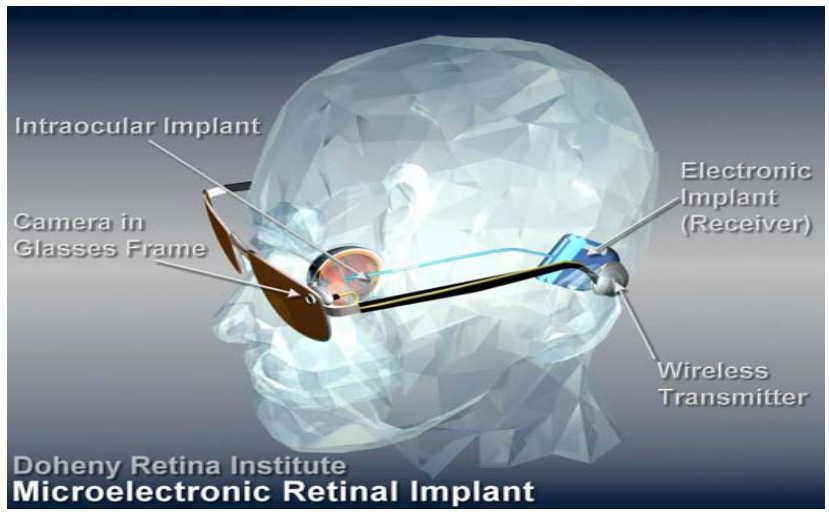
Cancer results from accumulation of multiple genetic changes in a cells.

Nanotechnology will allow earlier detection and prevention (Year 0)

Interfaces with human cells and sensors

Ex:

- J. Heath (Caltech): Sensors for subcellular processes & computer of the size of a cell: **continuous monitoring and interaction**
- Robert Greenberg: **Interfacing to the sensory human nervous** system via chemical, electrical, mechanical, magnetic signals
- David Reinken (UC Irvine): **robotic devices for training** of movements after neurologic injuries
- James Gram (TAMU): **memory with spinal cord**
- **Various prosthesis**: may increase visual (infrared, X-ray, etc.), audio, smelling, tactile, nerves, or other capacities
- Chemical-mechanical **macromolecular machines**
- Doheny Retina Institute: **artificial retina**



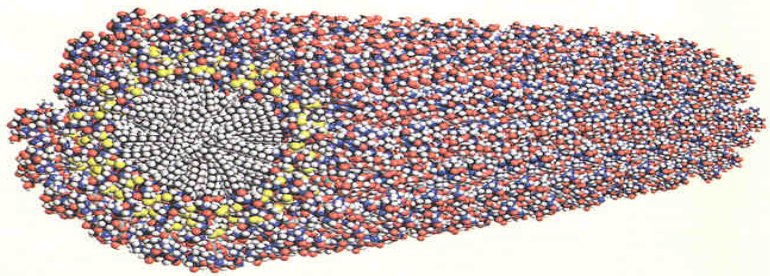
SELF-ASSEMBLED ARTIFICIAL BONE OR NEURAL CONNECTION (S. Stupp, NU)

SCIENCE & TECHNOLOGY

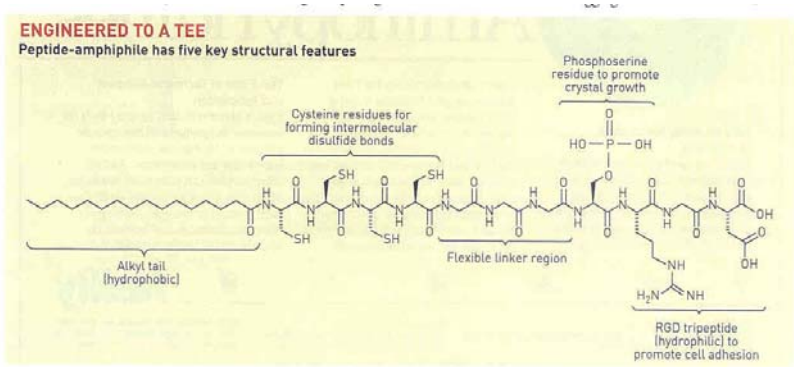
MIMICKING THE WAY NATURE GROWS BONE

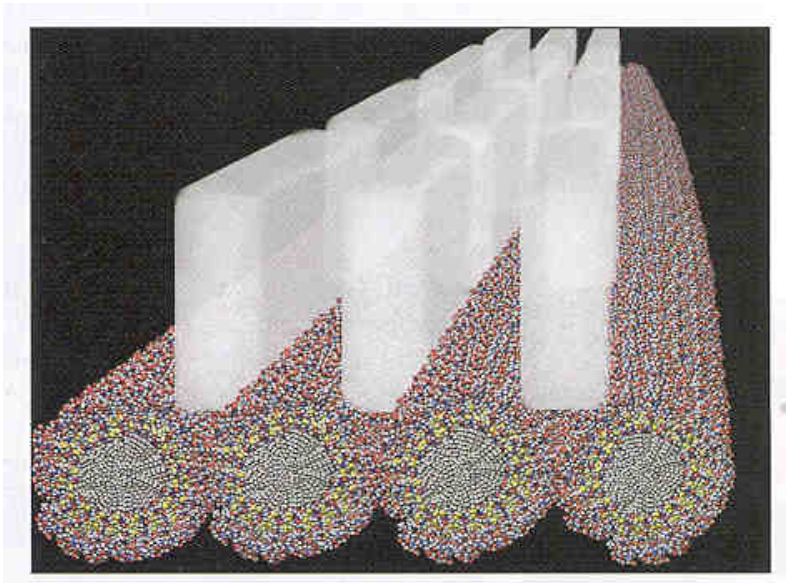
Exquisitely designed molecules assemble into nanofibers that promote the growth of mineral

R

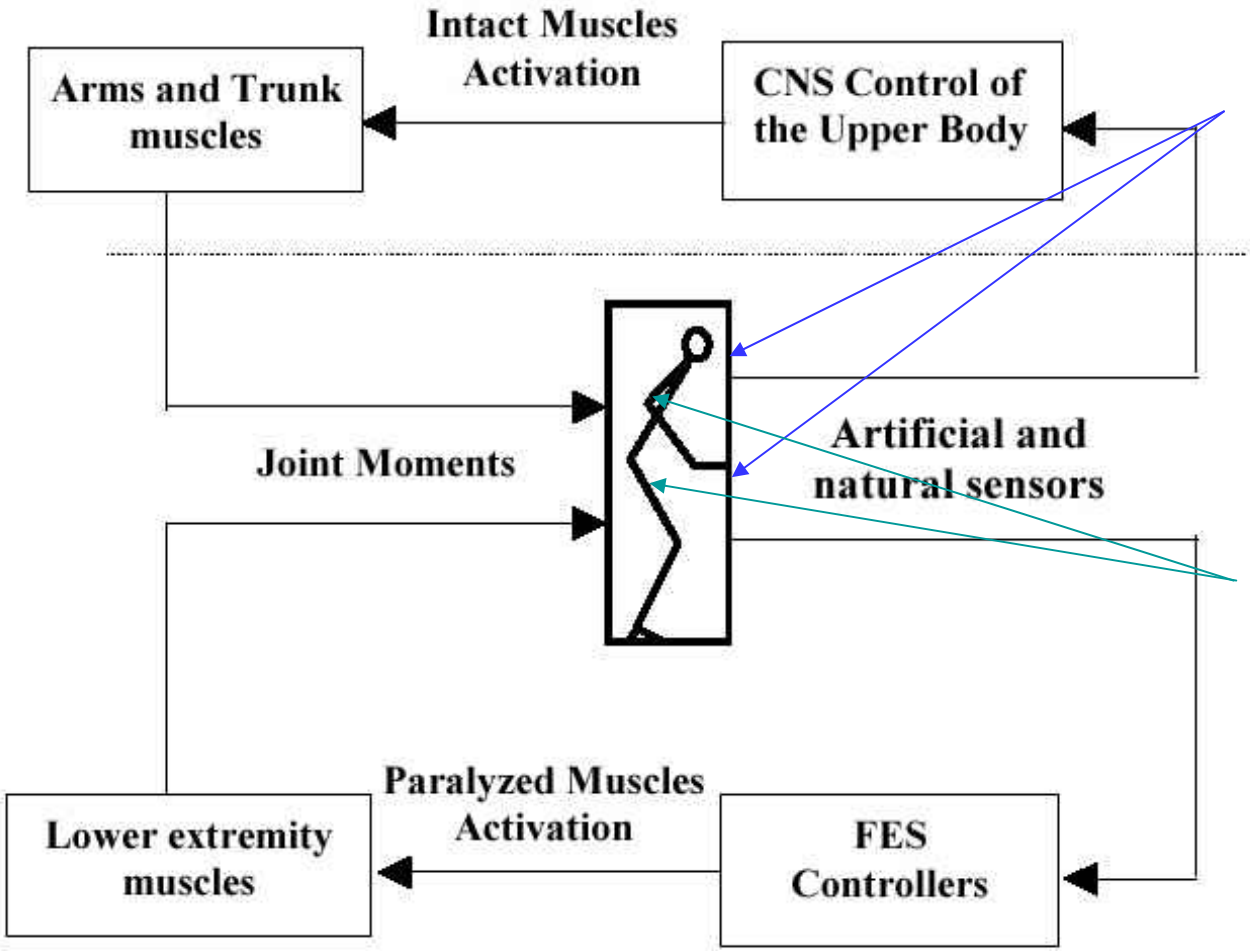


PROGRAMMED ASSEMBLY Molecular model of the peptide-amphiphile (top) reveals its overall conical shape going from the narrow hydrophobic tail to the bulkier peptide region (carbon is black; hydrogen, white; oxygen, red; nitrogen, dark blue; phosphorus, pale blue; sulfur, yellow). Below pH 4, the amphiphile molecules assemble themselves into long cylindrical micelles, or nanofibers. The bulkier peptide region, which contains the RGD sequence and phosphoserine, lies close to the fiber surface.



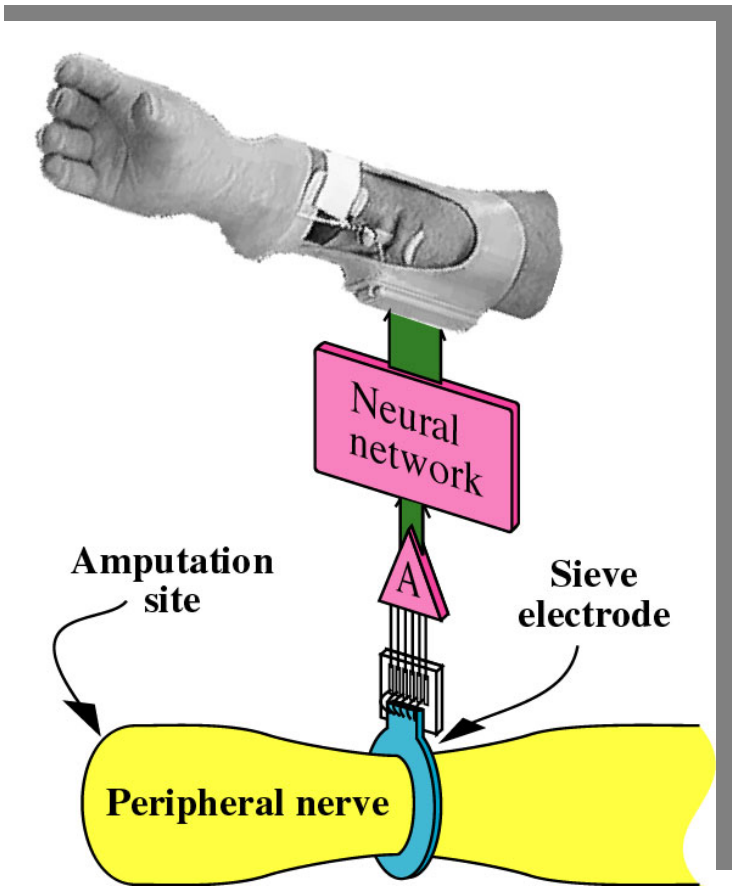


Can we connect nanoelectronics to biology?
What is currently possible?



ARTHAND PROJECT: Mind controlled prosthesis

Lund University, 2003



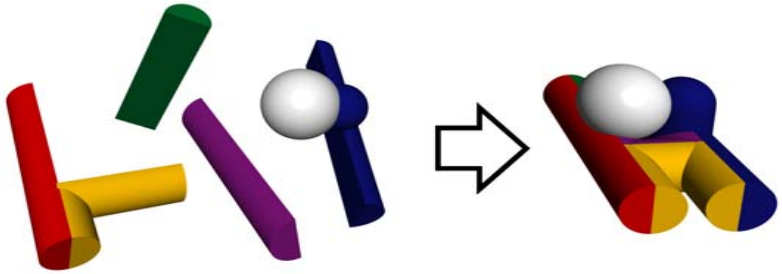
Neurobiology
Neurophysiology
Biomaterials
Learning models
Rehabilitation and Sensory feedback

C. Enhancing Group and Societal Outcomes (including new technologies and products)

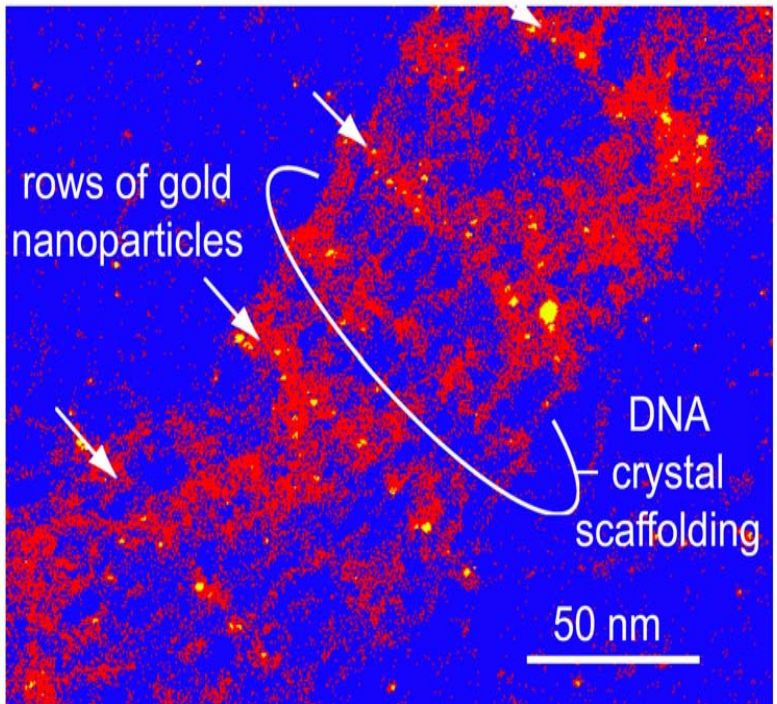
- **Methods for enhancing group interaction and creativity**
- **Cognitive engineering and enhancing productivity**
- **Revolutionary manufacturing processes, products and services.** Ex: hybrid manufacturing, bio-inspired nanoelectronics, bio-robotics (muscles), “aircraft of the future”, bio-chem lab on a chip, adaptive and emerging intelligence systems, multiphenomena software from the nanoscale, pharmaceutical genomics, neuromorphic engineering, intel. env.
- **Networked society, with bio-inspired culture**
- **Business as agents of change for human perfomance**

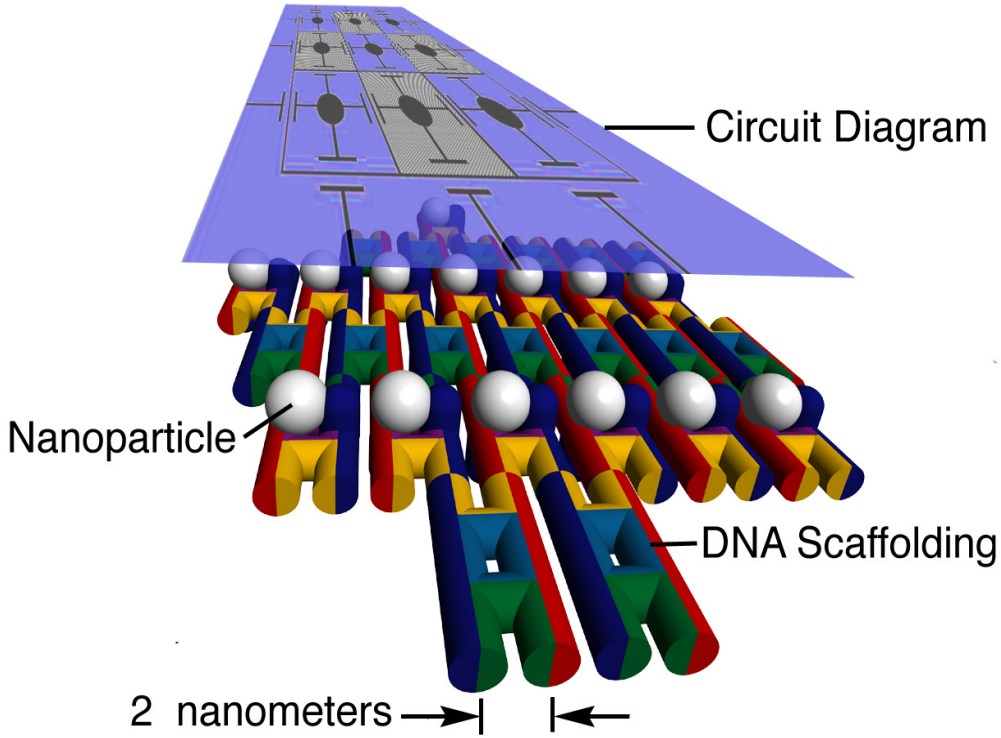
Three-dimensional assembling - synergism NT - BT – IT

U. of Minn., R. Kiehl, J. Nanoparticle Res., 2002



Selfassembled DNA synthetic strands and nanoparticles

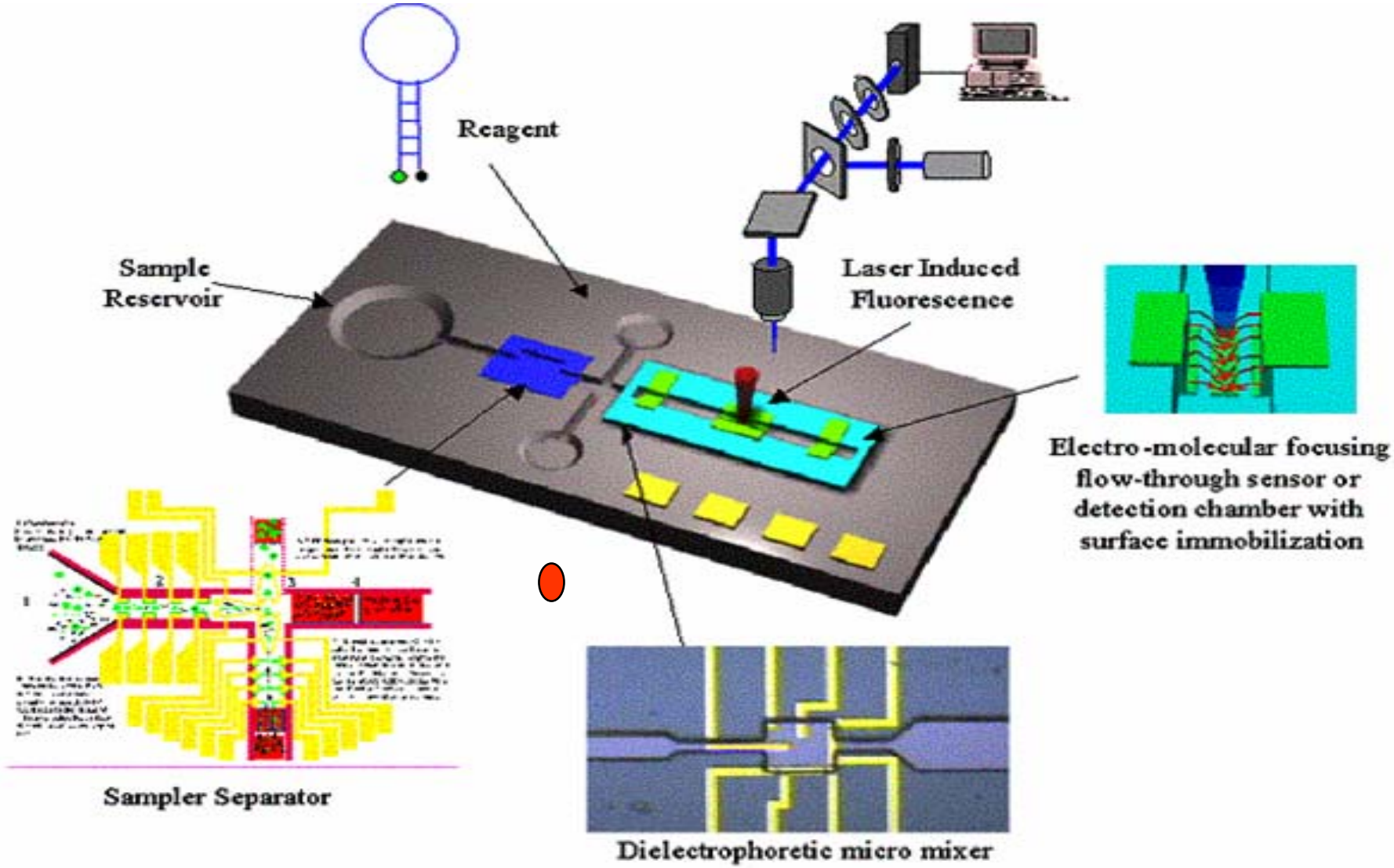




3D architecture
for a nanoscale electronic circuit

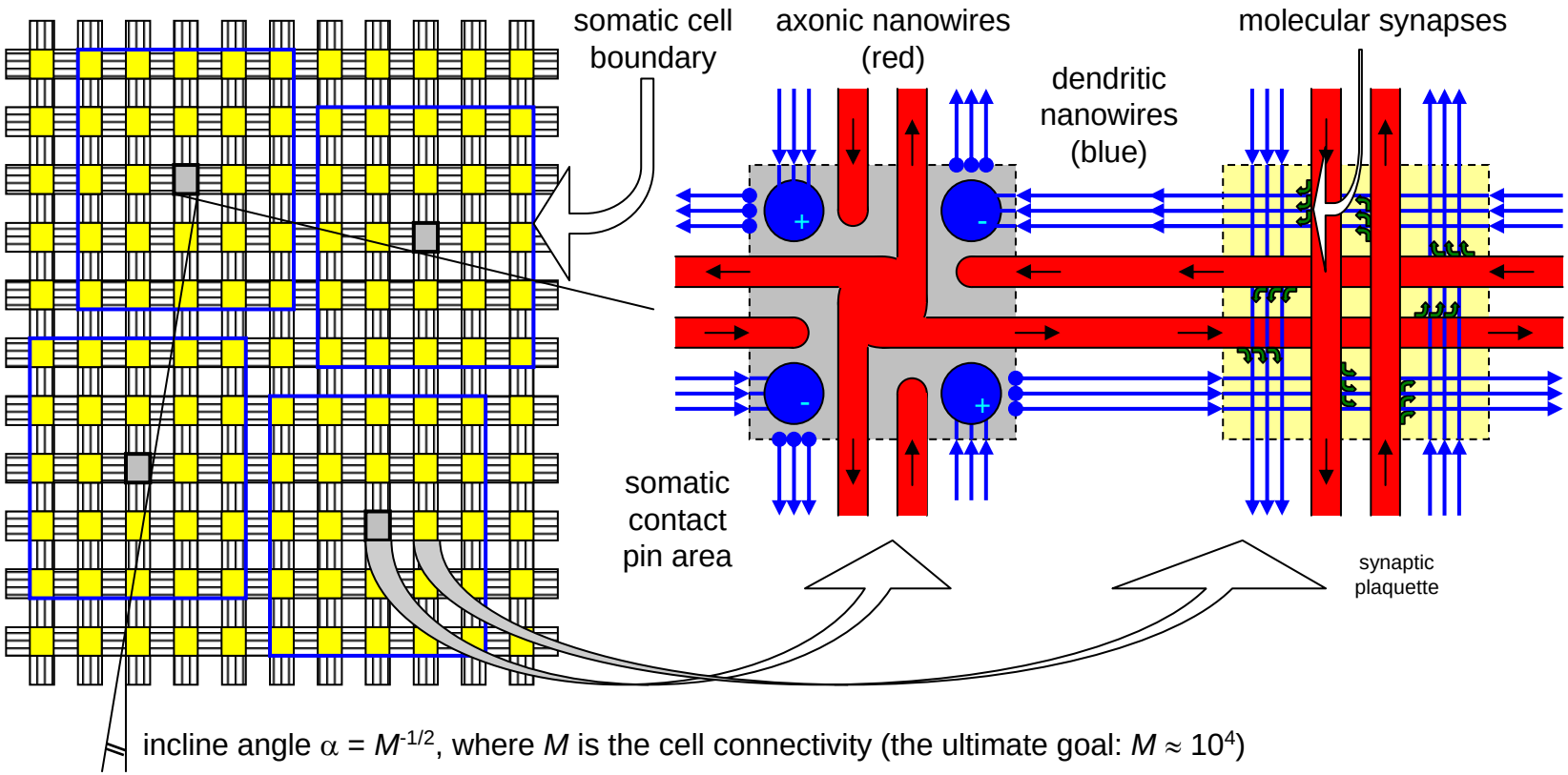
Ex: Biochips as integrated multifunctional systems.

Detection of illnesses using saliva: the detection chamber that includes the different ligand for simultaneous optical detection of multiple analytes (**D. Wong, C.-M. Ho, UCLA)**



Ex: Nanoscale Single-Electron Switching Arrays for Self-Evolving Neuromorphic Networks

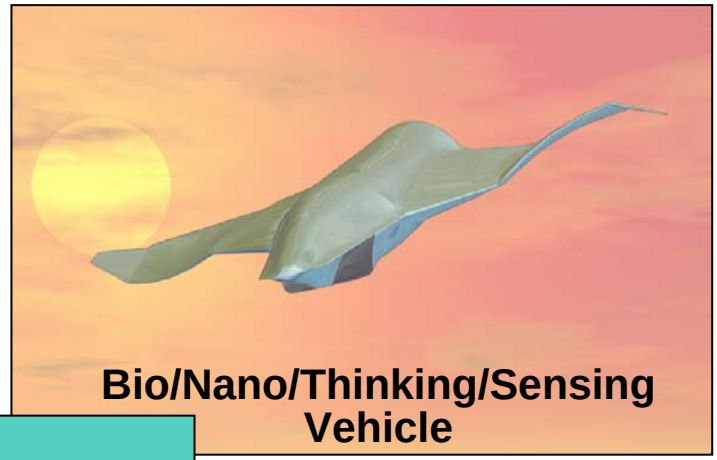
K. Likharev, SUNY Stony Brook, 2002



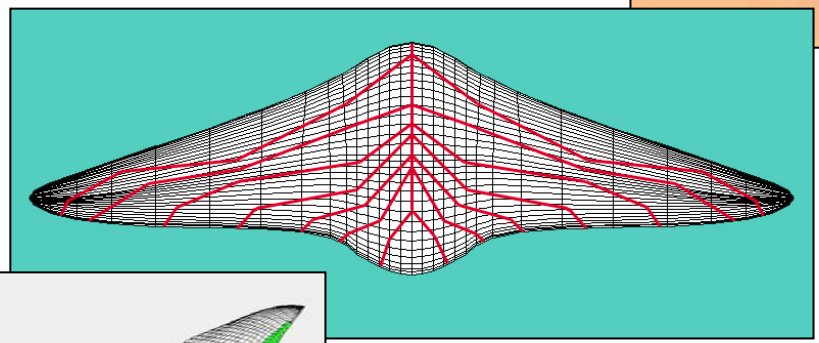
This architecture allows to combine high density CMOS-based somatic cells (up to 10^8 per cm^2) with extremely high density of single-electron latching switches working as synapses (up to 10^{12} per cm^2) necessary for our "final" goal: placing a hardware analog of a mammal cerebral cortex on a 10×10 cm^2 silicon area.

Towards Advanced Aerospace Vehicles: "Nature's Way"

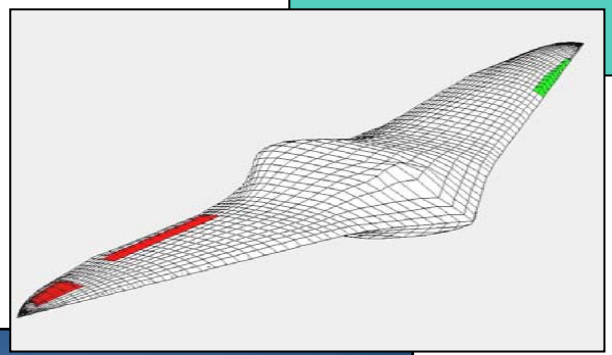
- Distributed self-assessment and repair
- Adaptive shape control
- Highly efficient propulsion
- Exploits Bio-Nano-Info technology revolution



Bio/Nano/Thinking/Sensing Vehicle



Self-Healing Structure with "Central Nervous System"



Smart Structure with Active Flow Control

Modern Advanced Metal Aircraft

- Ultra Safe
- Whisper Quiet
- "Zero" Emissions
- Extreme Maneuverability
- High Survivability
- Ultra Low Fuel Burn

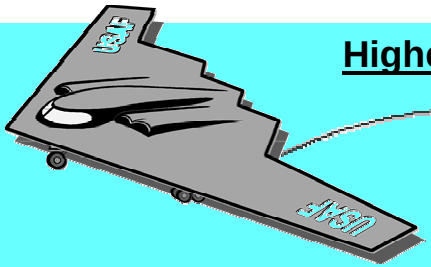
Advanced Technology Development

Time

D. National Security

- **Enhancing physical and mental capacity of a soldier**
- **Enhancing readiness, and threat anticipation tools**
- **Globally linked detection devices**
- **Uninhabited combat vehicles**

Several Military Aspects of National Security and NBIC



Higher performance platforms (stronger, lighter weight materials)

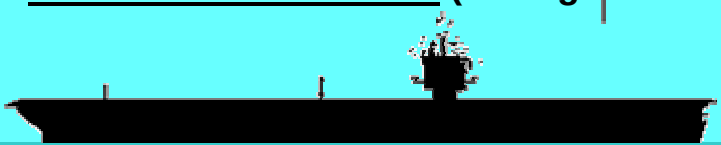
Enhanced sensing

Optical (components from nanostructures)
RF/microwave (materials, components)
Chemical/biological (at nano-level)
Nuclear (non-proliferation treaty monitoring)

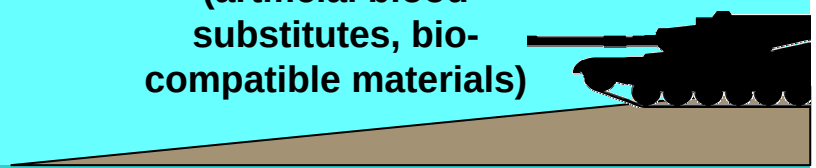
Enhanced Human performance (performance monitoring, readiness, aids to human sensing)

Remediation (chemical/biological detoxification)

Information dominance (through information technology)

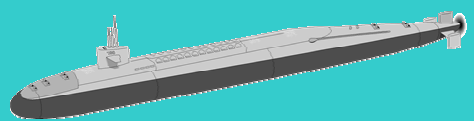


Battlefield casualty care (artificial blood substitutes, bio-compatible materials)



Reduced manpower requirements (through automation)

Safer operations (use of robotics for hazardous tasks)



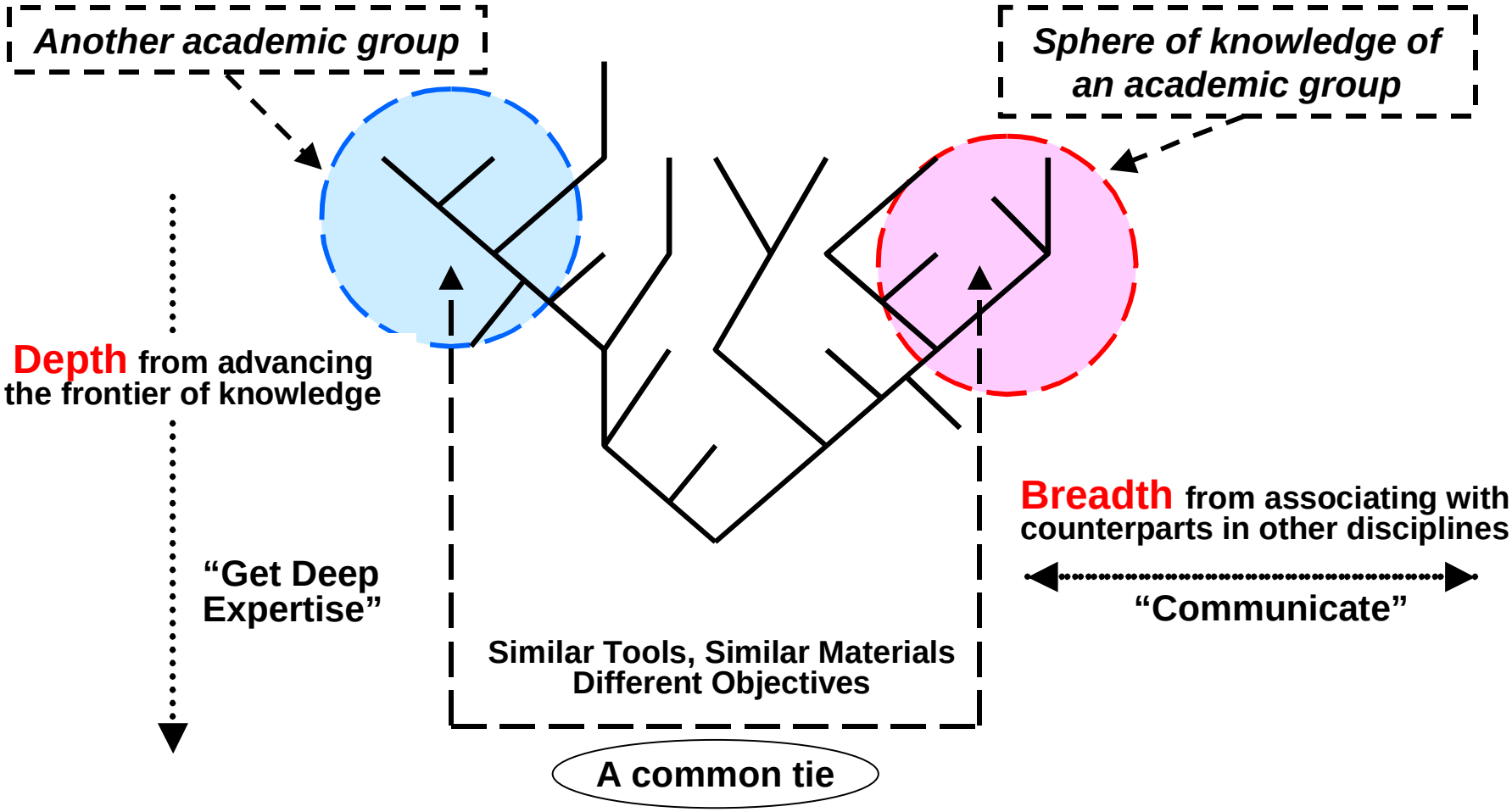
Lower life-cycle costs (improved materials, coatings, condition-based maintenance)

(NBIC Report, 2002)

E. Unifying Science and Education

- **Unifying science from the nanoscale and integrative principles**
- **Cognitive, civic, and ethical changes in a networked society**; Developing information systems and "science of intelligence" neurons, individuals, groups and society; Improving visual language
- **Breadth, depth, "trading zones,"** and reshaping education at all levels
- **Using NBIC technologies in education**
  Ex: Nano Kids, Molecularium, Virtual AFM
- **Changing the human culture**

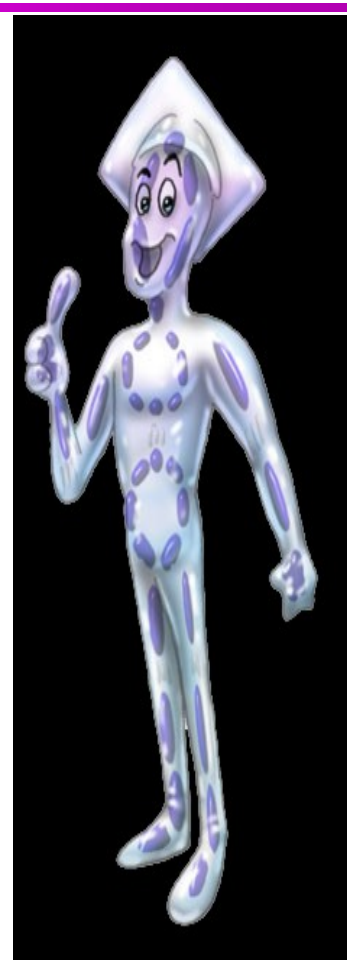
Combining “depth with breadth” in NBIC education and research



(NBIC Report, 2002)

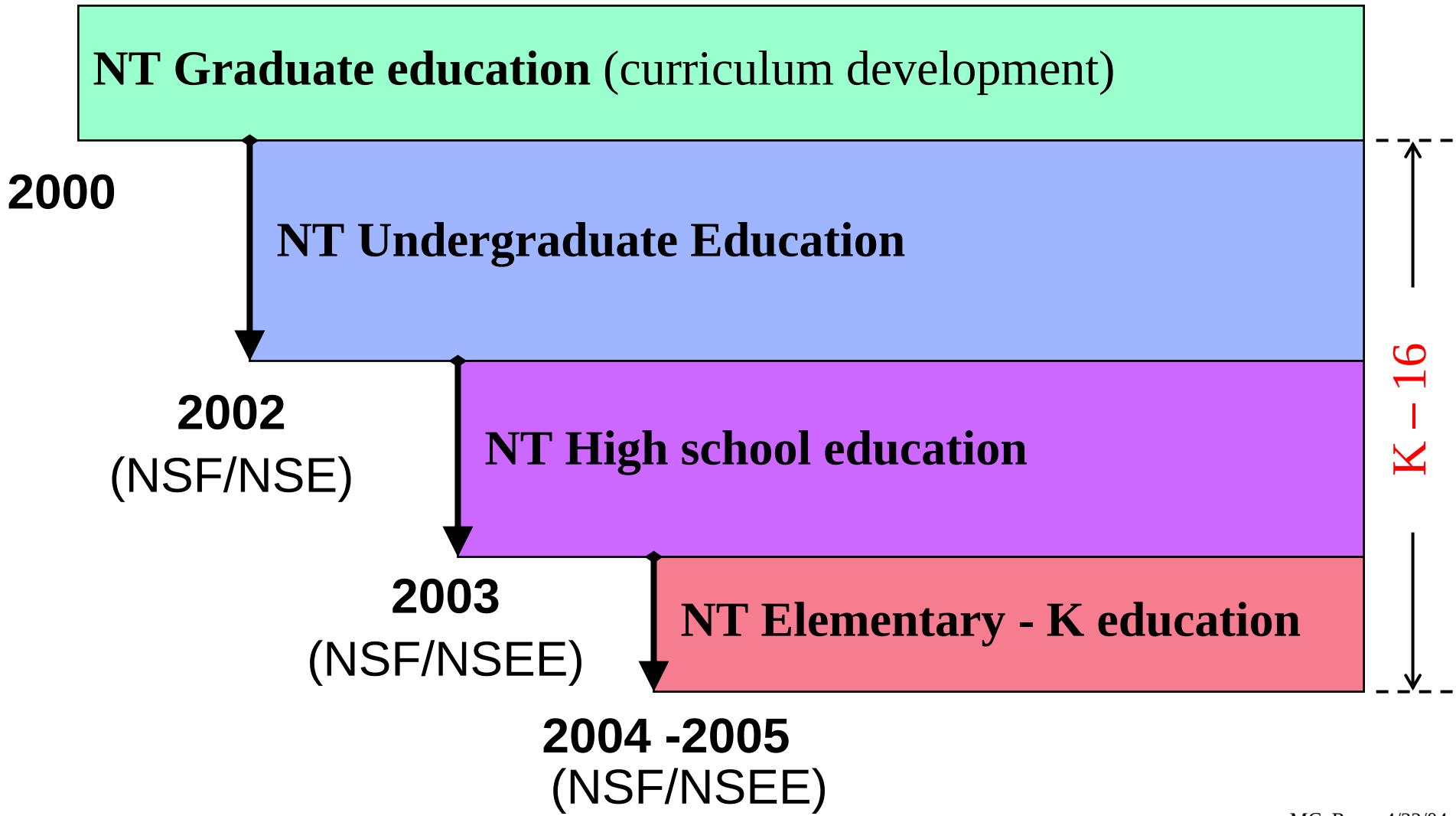
Ex: Objectives for nanotechnology education (NNI)

- Fundamental understanding from the nanoscale:
  moving the foundation of learning from "microscale" to "nanoscale"
- Sharing similar concepts in various disciplines and relevance areas:
  unifying concepts earlier in education
- **"Reversing the pyramid of learning"**: learning first unifying concepts of matter/ biology/ information systems, and then averaging techniques specific to each discipline
- **Combine "depth" with "breadth"**
- **Broader accessibility and motivation to S&T**
- **Engineering has an increased role** because of its interdisciplinary, integrative, system approach and transforming characteristics. Nanotechnology deals with systems.



"Reversing the pyramid of learning": learning first unifying concepts of matter/ biology/ information systems, and then averaging techniques

Ex: Introducing earlier nanotechnology education (NSF)



F. Distributed organizations and business

- New concept for NBIC, distributed, products on demand; decentralization of existing organizations
- Current social, educational and organizatoric theories may become irrelevant and must be reformulated
- Distributed production: energy, manufacturing, knowledge
- Clusters of “technology parks”
- Build new interdisciplinary competencies, partnerships
- International dimension increases in importance

G. Policy implications of NBIC for R&D and new investments (1)

1. Establish a **broad/long-term S&E framework** for accelerated techno-economical development using NBIC
2. **Support NBIC integration** though long-term strategic planning for each major trend (ex: NNI, ITR, Biomedical; Challenges: cognition, integration); **Address the gaps**
3. Prepare the new NBIC **S&E platforms**, through priorities of infrastructure investments and productive incentives. Include development of nomenclatures and definitions
4. **Reduce the delay between technological development and societal response**. The risks of S&E developments should be evaluated in the general context of potential benefits and pitfalls in the long term

Policy implications of NBIC for R&D and new investments (2)

5. Identify **new evaluation criteria** to include the NBIC progress and accumulations in the national infrastructure
6. **Responsible development** of NBIC: respect human condition and right to access/use R&D outcomes
7. Revise **earlier education and training**
8. **Promote partnering** academe-industry-government in advancing NBIC, through joint fora, funding
9. Develop **anticipatory responses** in the legal system and patent system
10. Use **global context & partnerships**

Responsible development of NBIC

- **Harmonious introduction of technology**
- **Respect human (integrity, dignity and welfare) and society (regulatory measures, support developing regions, . .) conditions**
- **Environmental, health and safety issues**
- **Anticipatory measures for standards, metrology, ethical and legal, socio-economic, and political aspects**
- **Research & commercialization and societal needs**

Converging Technologies Bar Association (CTBA)

- Dialog with legal community, public awareness
- Education and reference material for the legal system
- Source of information on implications of NBIC
- Support creation of converging technologies corridors
- Advocate policies, regulations and legislation. Anticipatory measures for the implications of NBIC

Harrington v. State

CBTA contacts:

www.convergingtechnologies.org

info@convergingtechnologies.org

Seed NBIC research activities in industry

(examples)

- **IBM**
- **DuPont**
- **HP**
- **Rockwell Scientific**
- **Intel**
- **General Electric**
- **Mobil**
- **Many entering this field**

International interest: US, Japan, EC, Korea, Switzerland, France, others

Few statements since 2002

- FY 2002 NNI Budget Request, WH/OMB:

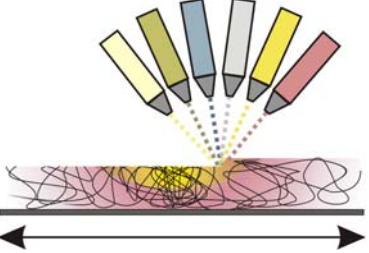
  Converging technologies from the nanoscale will stimulate the economy

- Greenspan, 2003

  About 70% of economic growth after the second war accelerated productivity

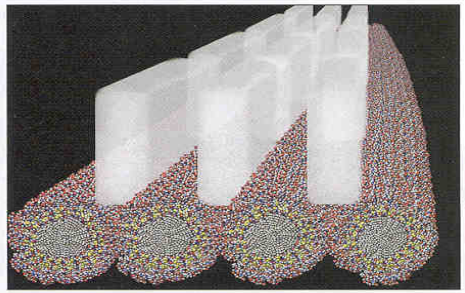
- Ardent Bement, Acting Director NSF, 2004

  Converging technologies used as a framework for research and education priorities



Seed NBIC research activities in Federal agencies since 2002

- **NSF** - **Framework for long term**: Coherence in education of S&T
  - Support NBIC related projects as exploratory research grants and several centers (Neuromorphic Engineering ERC Caltech, three NSECs); NBIC from nanoscale
  - Aspects of nano-bio-info as components in NSE, ITR, BE
  - Initiative on societal implications of converging technology; and learning
- **NASA** - **Integrative R&D strategy**
  - Centers on nano-bio-info for cells at UCLA, electronics at Purdue University, and materials at TAMU/Princeton
- **DOE, DOD** - **Various programs**: improving human performance
- **NIH and USDA** – **Various programs**: nanobiotechnology + I, C
- **EPA** - **Future planning**, include life-cycle environment issues



Seed R&D programs since 2002

- Converging S&E components in: **Nanoscale Science and Engineering** (2002- 2004), **ITR**, **Biocomplexity**, **Sensors**
- Improving human performance in **NSF Human and Social Dynamics (**2003-2004)
- NSF-NIH on computer **simulation of the brain**
- NSF centers for "**learning to learn**"
- NSF **SBIR** focus on converging technologies (2003-2004)
- NASA **improving human performance** for space exploration, and nano-bio-info programs
- DARPA **nano-bio-info-cognitive** research focus
- About ten **NSF and NASA centers** on domains of NBIC
- Nanobiotechnology in conjunction with 'I' and 'C' at **NIH**

DARPA programs for FY 2003 (ex.)

- **Brain Machine Interface**

  Communicate with the world directly through brain integration and control of peripheral devices and systems

- **Metabolic Engineering**

  Develop methods for controlled metabolism in cells, tissues, organs, and organisms needed by the U.S. military population

- **Exoskeleton for Human Performance Augmentation**

  Technologies to remove the burden of mass and increase the soldier's strength, speed, endurance

- **Continuous Assisted Performance**

  Prevent the degradation of cognitive performance caused by sleep deprivation

NASA programs for FY 2003 (ex.)

- **Goals for future NASA systems**
  autonomous, resilient, ultraefficient, evolvable, highly distributed, self-sufficient (attributes of biosystems, to be done with NT, IT and CT)
- **Revolutionary products**
  human sensor, plane of the future, improving human performance of astronauts
- **NASA-NCI at convergence of nano-bio-info-health**
- **Four academic research centers based on integration**

NNI centers of excellence with NBIC research and education components (ex.)

Center Name	Funding Agency	Institution
Nanoscience in Biological and Environmental Engineering	**NSF** (NSEC)	Rice University
Integrated Nanopatterning and Detection	**NSF** (NSEC)	Northwestern Univ.
Directed Assembly of Nanostructures	**NSF** (NSEC)	RPI
Nanobiotechnology	**NSF** (STC)	Cornell University
Institute for Cell Mimetic Space Exploration	**NASA**	UCLA
Institute for Intelligent Bio-Nanomaterials & Structures for Aerospace Vehicles	**NASA**	Texas A&M
Bio-Inspection, Design and Processing of Multi-functional Nanocomposites	**NASA**	Princeton University

NIH

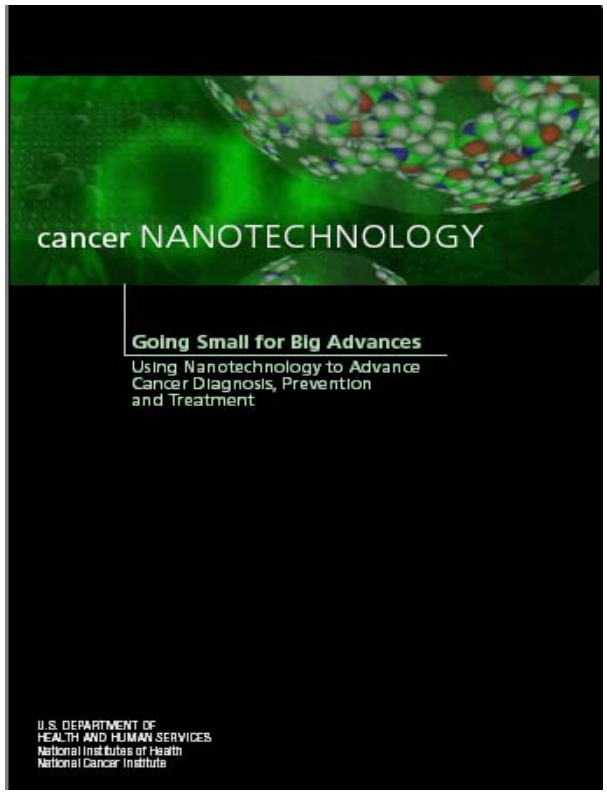
NANOBIOTECHNOLOGY RESEARCH SUPPORT, IN CONJUCTION WITH IT AND NEUROLOGY

BECON

Technology Development for Biomedical Applications: foster partnerships between the nanotechnology and the cancer, heart, lung, blood, and sleep disorder R&D programs and communities

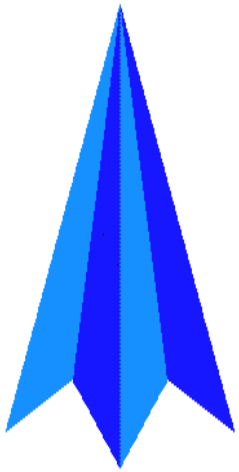
Examples:

- Molecular Analysis of Cancer
- Saliva/Oral Fluid-Based Diagnostics
- Functional Tissue Engineering of Musculoskeletal Tissues and Cornea
- Novel Technologies for *in vivo* Imaging
- Development of Novel Drug and Gene Delivery Systems and Devices

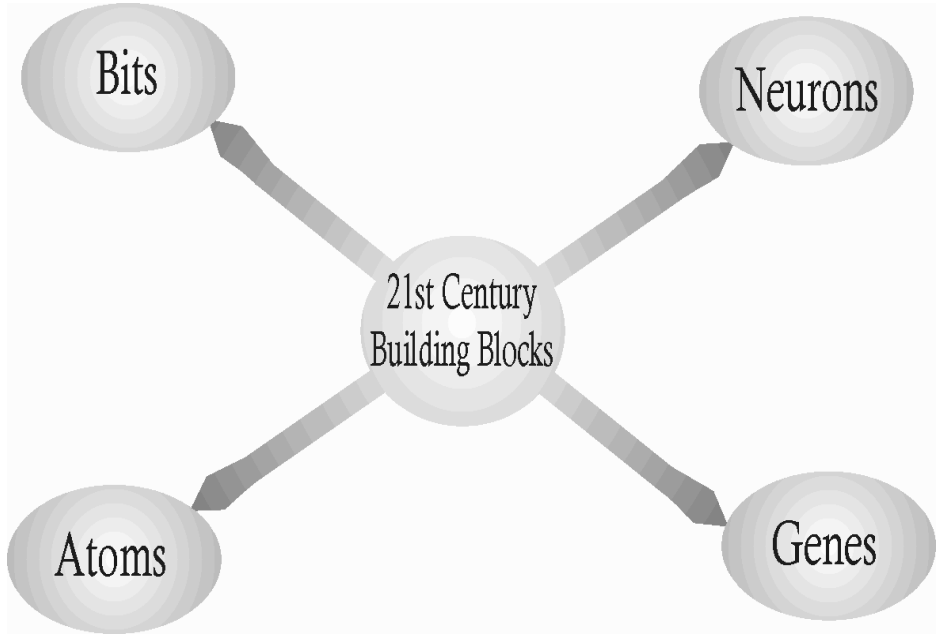


Several NBIC challenges and policy decisions

- **Create science and technology platforms for NBIC; Prepare a national network for earlier NBIC education**
- **Develop hybrid manufacturing, neuromorphic engineering, and global networking**
- **Understanding the nervous system, and the connection to mind, behavior, education and work productivity**
- **Develop capacity to anticipate and manage future opportunities and risks for deliberate and responsible developments**
  - **Respecting human integrity and dignity**
  - **Include NBIC contribution in other large programs**
  - **Suit demographics and sustainable development**
- **Cultural implications; Public understanding and participation**



Convergence



If the *Cognitive Scientists* can think it
the *Nano* people can build it
the *Bio* people can implement it, and
the *IT* people can monitor and control it

From a workshop participant (W.A.W.)

Related references

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